GRAVITATIONAL RADIATION FROM MERGERS OF BLACK HOLE–NEUTRON STAR BINARIES

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Angular momentum loss via the emission of gravitational waves must eventually drive compact binaries containing black holes and/or neutron stars to coalesce. The resulting events are primary candidate sources for detectors such as VIRGO and LIGO. We present calculations of gravitational radiation waveforms and luminosities for the coalescence of a black hole-neutron star binary, performed in the quadrupole approximation using a Newtonian smooth particle hydrodynamics code. We discuss the dependence of the waveforms and the total emitted luminosity as well as the final configuration of the system on the initial mass ratio and the degree of tidal locking.

1 Introduction

According to theoretical estimates[4,9] some stellar-mass black holes are expected to be formed in binary systems with neutron stars with which they will coalesce at a rate $\geq 10^{-6}$/year per galaxy. In addition to being candidate sources for gravitational wave detectors, such mergers have been suspected[8,3] to give rise to the observed cosmic gamma-ray bursts.[1] We present a summary of the results of our Newtonian hydrodynamic simulations of the interaction of a neutron star with a black hole in a tight binary. The results vary with the mass ratio of the two objects and depend markedly on whether or not the rotation of the neutron star is synchronized with the orbital motion.

We find a significant tidal transfer of angular momentum from the accreting matter back to the mass donor—as a result the neutron star survives mass transfer in nearly all the cases we have investigated. This greatly extends the duration of the coalescence, the gravitational signal will not be limited to one chirp.

2 Numerical Method

The three dimensional Newtonian numerical simulations presented here have been performed using a smooth particle hydrodynamics (SPH) code. This technique[7] is fully Lagrangian and eliminates the need for a grid to carry out calculations. A tree algorithm was implemented to optimize the computation of long-range interactions[6]. The neutron star is modeled as a $1.4 M_\odot$ polytrope of index Γ=3 and unperturbed radius R = 13.4 km. We use 16,944

particles of unequal masses. The black hole is represented[5] by a point mass with an absorbing spherical boundary at the Schwarzschild radius. The gravitational radiation waveforms were computed in the quadrupole approximation. In the dynamical calculations presented here, radiation backreaction was not included.

3 Results

For a tidally locked binary with a mass ratio of unity ($q = 1$) the amplitude and frequency of the gravitational waves decrease after the initial rise at the onset of mass transfer (Fig. 1a). This is because the polytropic core survives the initial encounter with the black hole and the final configuration of the system is an apparently stable binary with a diminished mass ratio of $q = 0.19$. Naturally, gravitational radiation will eventually bring the neutron star into Roche–lobe contact again.

In contrast with our preliminary results,[2,5] our current simulations, performed with increased resolution, show that a torus lasting for a few orbits appears around the black hole (Fig. 2). There is a baryon–free axis present throughout the simulation (down to our resolution of $\sim 10^{-4} M_{\odot}$).

For a lower mass ratio of $q = 0.8$, again in a tidally locked binary, the system also undergoes mass transfer on an orbital time scale, but now no torus forms, as all the material stripped from the neutron star is directly accreted by the black hole. Figure 3 shows the gravitational wave luminosity for the two cases mentioned above, as well as for a double neutron star merger.[5,10] Note that the three cases lead to qualitatively different results.

For an even lower mass ratio, the nature of the event is different. There is now a brief episode of Roche–lobe overflow from the neutron star onto the black hole, in which a modest amount of mass is transferred and the binary separation increases. For this tidally locked case, one can no longer say that the hydrodynamical effects play a predominant role, since the time scale τ_{GW} for orbital decay due to angular momentum loss to gravitational waves is shorter than the time of mass transfer in the present calculation. Inclusion of radiation reaction will change the detailed shape of the waveforms. Nonetheless, we present (in Fig. 1b) the results for $q = 0.31$ (corresponding to a black hole mass of $4.5 M_{\odot}$) to contrast the case of a tidally locked binary[11] with the case when the neutron star has zero spin and is initally spherical. In the latter case, the orbital decay proceeds on a time scale comparable to τ_{GW}, there is rapid mass transfer and the polytropic core again survives the encounter to be transferred to a higher orbit.

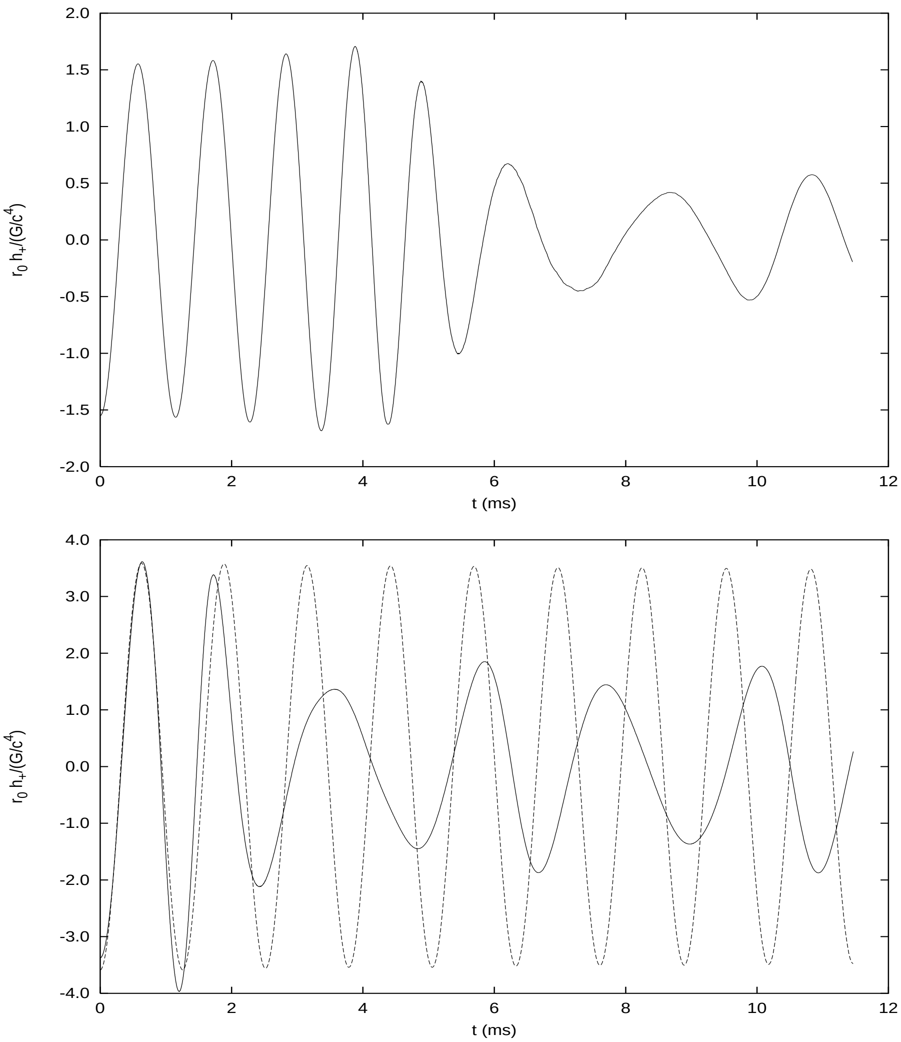

Figure 1: Gravitational radiation waveforms for an observer placed at a distance r_0 away from the center of mass along the rotation axis of the black hole–neutron star binary for a) (top panel) $q = 1$; b) (bottom panel) $q = 0.31$ with tidal locking (dashed line) and no tidal locking (solid line).

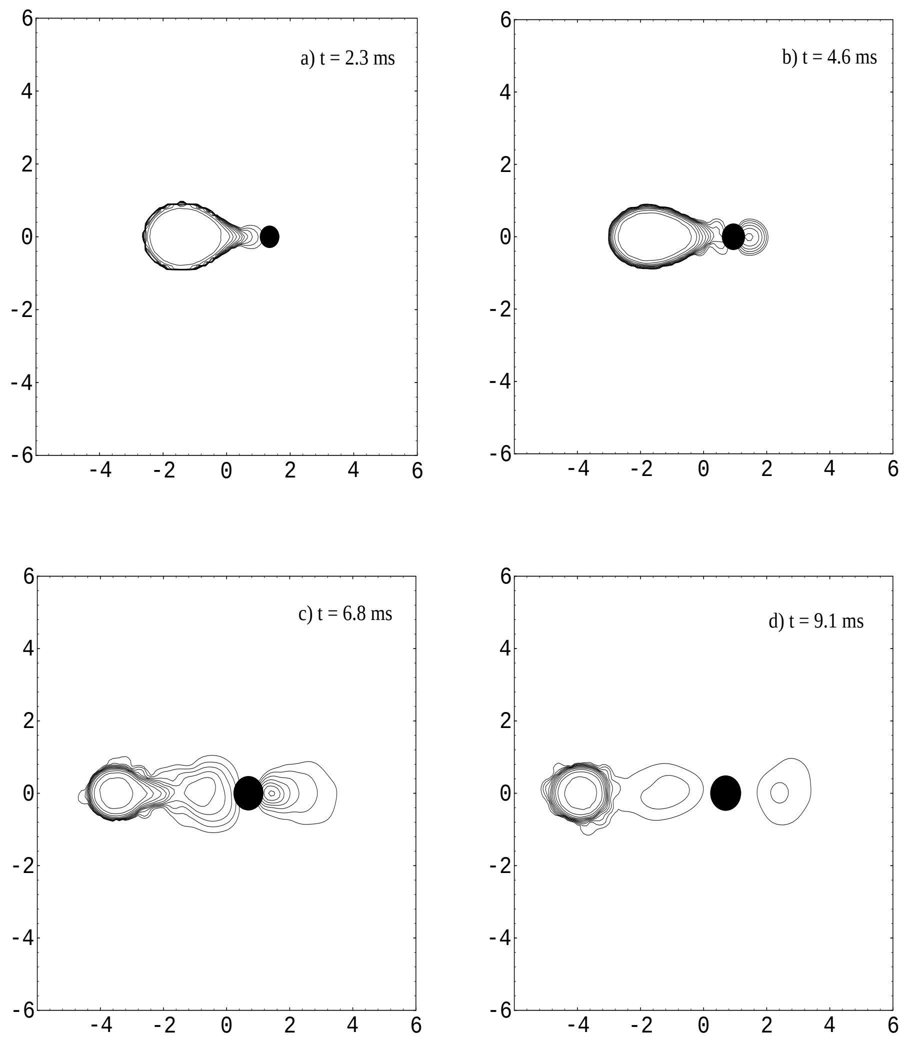

Figure 2: Density contours in the meridional plane at various times during the dynamical coalescence of the black hole–neutron star binary with mass ratio $q = 1$. There are eleven logarithmic contours evenly spaced every 0.25 decades, with the highest density contour at $\rho = 2.0 \times 10^{14}$g cm^{-3}. The unit of distance is the unperturbed stellar radius R. The black disk represents the black hole (increasing in mass).

Acknowledgments

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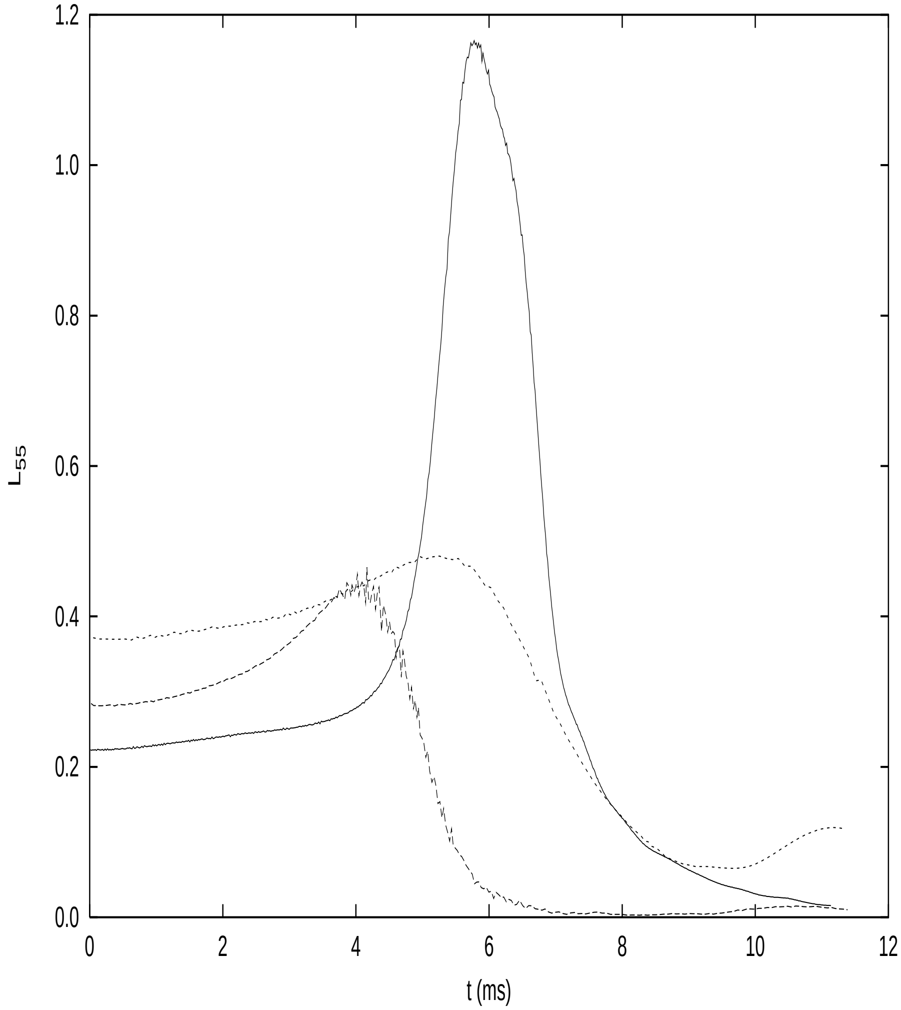

Figure 3: Gravitational wave luminosities, $L_{55} = L/(10^{55}\mathrm{erg\ s}^{-1})$, for the double neutron star coalescence with mass ratio $q = 1$ (solid line), as well as for the black hole–neutron star coalescence with $q = 1$ (dashed line) and $q = 0.8$ (dotted line).

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11. A waveform we presented previously in fig. 3 of ref. 2 corresponded to a $q = 0.31$ configuration which had not been properly tidally locked.